MICROMACHINED CMOS MAGNETIC FIELD SENSORS WITH LOW-NOISE SIGNAL CONDITIONING

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ABSTRACT

Two original electromechanical magnetic sensors have been developed using fully industrial fabrication process that relies on bulk wet etching of CMOS dies. The first device uses the Lorentz force to actuate a U-shaped cantilever beam, while piezoresistive polysilicon gauges convert the beam bending into electrical signal. A 2µT sensor resolution has been achieved, making this device suitable for earth magnetic field measurement. The second prospective device uses a ferromagnetic material deposited on top of a free standing mechanical frame. Such approach leads in the design of a passive sensor that does not require any electrical power for actuation.

INTRODUCTION

The market of CMOS magnetic sensors is currently dominated by Hall effect devices, which have been under constant improvement for years [1]. Cost-effective batch fabrication, integration with electronics and demonstrated reliability are the key reasons for this success. The known limitations of Hall effect CMOS sensors are their out-of-plane sensitivity, the temperature drift and finally, both offset and noise level that limit the sensor resolution. New CMOS devices such as Magneto-transistors or vertical Hall devices are under study in order to provide in-plane sensitivity and 2-axis measurement, that is required for several applications [2].

This paper introduces two new CMOS magnetic sensors which use mechanical structures as sensing elements. The first device is based on an optimized cantilever beam actuated by means of the Lorentz force. It provides in plane sensitivity for 2-axis measurement capability. The second sensor relies on pure magnetic actuation of electrodeposited ferromagnetic layer. In this case, no electrical power is required for actuation. Both sensors take benefit from cost-effective CMOS batch fabrication and collective bulk micromachining. Since piezoresistive gauges are used to measure mechanical deformations, offset and temperature drift are easily overcame. Both design, fabrication and characterization of those sensors are addressed with particular interest on signal processing for amplification and noise filtering.

DESIGN & MANUFACTURING APPROACH

CMOS/FSBM Technology

As far as we know, the unique solution to achieve monolithic CMOS electromechanical devices is to apply micro-machining post-processes on foundry-finished wafers. The Front Side Bulk Micro-machining (FSBM) post-process allows the fabrication of mechanical structures using a silicon wafer issued from a standard CMOS industrial process. This cost-effective technology does not require any additional lithography step since etched areas are defined by openings in the dielectric layers during IC fabrication. It can be easily addressed in Europe through Multi-Project Wafer services [3]. We have been using this fabrication facility for several years and we have observed a high level of process repeatability.

Design approach

From our point of view, a CMOS microsystem is similar to a standard mixed-signal ASIC. It includes mechanical cells (beams, membranes…) among other standard analog cells such as resistances or capacitors. In this context the whole system design is supported by standard EDA CAD tools including schematic capture, system level simulation and fabrication masks layout edition. Considering electromechanical components, this approach supposes that basic structures have been previously characterized and translated into a standard cell library, with associated symbols, simulation models and layout synthesis helps.

The structural materials of CMOS MEMS devices are limited to existing dielectrics, polysilicon and metals. Material properties are fixed for the sake of integrated electronics and important mechanical parameters such as material density, Young's modulus or residual stresses are not yet available for MEMS designers.

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Using CMOS and FSBM, we have developed and reported [4] a global MEMS design approach. The system design in standard CAD tools is supported by Analog HDL models, which have been written accordingly to behavioral modeling and experimentally validated.

LORENTZ FORCE MAGNETIC SENSOR

The proposed magnetic field sensor is based on the interaction between the magnetic field under measurement and a known current flowing into the device itself (current loop).

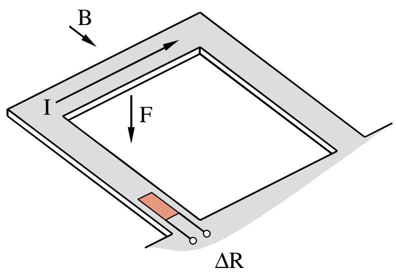

Fig. 1: Magnetic field sensing principle.

The basic mechanical structure (Figure 1) consists in a U-shaped cantilever embedding an aluminum planar coil. The coil is supplied with an electrical current *I* that can be continuous (static mode) or alternative (resonant mode). When an external magnetic field *B* is present, the cantilever beam is therefore deflected due to the action of the Lorentz force *F* applied to its free side. The Lorentz force is given by:

$$F = I \cdot B \cdot W_C$$

Where *Wc* (500µm) represents the dimension of the cantilever free standing edge placed in a perpendicular magnetic field. Finally, Polysilicon strain gauges are located into the mechanical structure close to anchor points in order to detect such deflections with a maximum sensitivity. For low cantilever bending, the relative change in the gauge resistance is then a linear function of the magnetic field.

Stand-alone U-Shaped cantilever performance

The major source of noise in resistors has thermal origins and appears as *white noise*. This noise spectral density function is therefore a constant over the frequency range, given by :

$$V_{noise}^2(f) = 4kTR$$

Where $k = 1.38 \times 10^{-23}\, J.K^{-1}$ is the Boltzmann's constant, *T* is the temperature in Kelvin and *R* is the resistor value in Ohms.

In our design, four $1.7k\Omega$ resistors are connected together in a Wheatstone bridge. Such bridge compensates for temperature variation and exhibits low offset voltage as a result of the good resistance matching. In this configuration, two resistors are actually gauges whereas the two others are fixed-value resistors deposited on the substrate. The bridge thermal noise at room temperature exhibits a root spectral density of:

$$V_{noise,\,rms}(f) = 10.6\, nV \big/ \sqrt{Hz}$$

Consequently, the total noise level over a 1MHz bandwidth is then $10.6\mu Vrms$. As a first conclusion for both static and resonant actuation mode, table 1 gives the sensor sensitivity accordingly with characterization results and the maximum resolution we can expect with a simple Wheatstone bridge and no signal processing over a $1MHz$ bandwidth.

	Static	Resonant
Sensitivity	14 mV/T	530 mV_{rms}/T
Resolution SNR = 1	760 μT	20 μT

Table 1: U-Shaped sensor performance.

Signal processing circuit

Looking at results of table 1, it is obvious that the best sensor performances in terms of sensitivity and resolution will be achieved using the resonant mode. In that case, the signal is restricted to the –3dB mechanical bandwidth around resonant frequency. The quality factor of such cantilevers is close to 100. The corresponding bandwidth is consequently only few hundreds hertz large.

It is a general rule to optimize noise performance that one should not design circuits for larger bandwidth than the signal requires. We thus have designed an amplification and filtering circuit in order to minimize total noise RMS value accordingly with the already restricted signal bandwidth. A schematic of the integrated system is presented on figure 2.

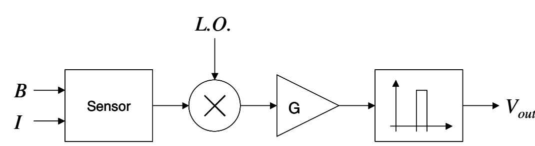

Fig. 2: Schematic of the measurement system.

In this circuit, amplification stage and band-pass filter are preceded by a multiplier, which is used to shift the amplifier input signal in the frequency domain. If the cantilever is used in resonant mode, this feature is required for adjustment purpose as long as it is difficult to precisely predict both sensor natural frequency and filter cutoff frequencies. In the case of a static actuation of the cantilever, the multiplier shall be used to shift the signal from DC to higher frequencies where the 1/f noise of amplifier becomes negligible (from the synchronous detection principle).

Simulations

Post-layout transient simulations and signals FFT of the magnetic field sensing system are presented on figure 3. Input signals are (i) the magnetic field step, (ii) the sinusoidal force voltage corresponding to the voltage applied across the planar coil generating the Lorentz force, and (iii) the local oscillator signal used by the multiplier. In order to shift the 10kHz cantilever resonant frequency to the 25kHz filter cutoff frequency, the local oscillator signal frequency has been fixed at 15kHz. Looking at FFT's the signal multiplication produce the expected frequency shift and the filter finally removes the undesired 5kHz peak.

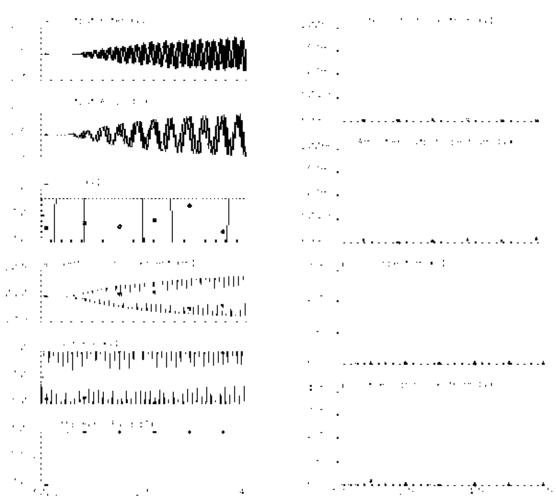

Fig. 3: System level simulations.

Noise Analysis

Figure 4 shows noise simulation results in terms of noise power spectral density for the complete signal processing circuit including the sensor gauges, the multiplier, the amplifier and the filter.

According to simulation results, the total noise level is about 8mVrms before filtering and 820µVrms when filtered with a 3kHz bandwidth. Since total amplification factor with mixer and square local oscillator is 660 , the sensitivity of the resonant sensor becomes 350Vrms/T with a 2µT resolution. Compared to the bare U-Shape device (table 1), sensitivity has been increased by a factor 660, while resolution has been improved by a factor 9.

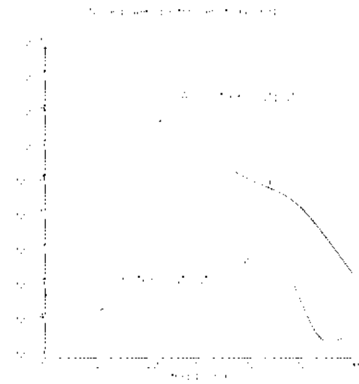

Fig. 4 :Noise power spectral density before and after filtering.

Fabrication and characterization

The sensing system shown figure 5 has been fabricated using a 0.6µm CMOS technology, a TMAH solution for bulk etching and a standard ceramic DIL24 package. The overall system area is 5mm^2 large. System characterization results are in good agreement with simulations. Especially, figure 6 shows the successful test results using the magnetometer as an electronic compass with a 1mA current for actuation. In absence of magnetic field, an ac offset of 200mVpp has been observed. This offset comes from capacitive coupling between actuation path and polysilicon gauges. It should be considerably reduced by using a intermediate metal layer to shield the gauge from the actuation path.

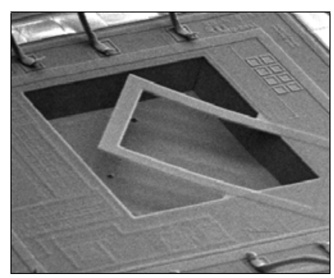

Fig. 5: The sensing system after bulk micromachining.

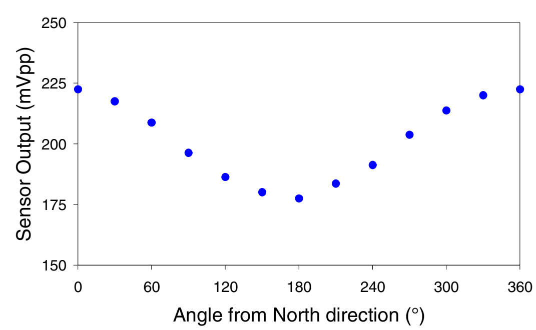

Fig. 6: Characterization result: Measurement of earth magnetic field over a 360° sensor rotation.

FERROMAGNETIC DEVICE

The second device involves both CMOS FSBM suspended structure and ferromagnetic material. Basic principles and modeling derive from previously reported work concerning ferromagnetic actuation of polysilicon structures [5]. The actual prospective prototype is based on the rotational actuation of a suspended frame with two rectangular magnets (figure 7). The mechanical actuation torque which is due to magnets shape anisotropies does not require any electrical power. This device may then be classified in the passive sensor category.

Device Fabrication

The bulk etching post-process is preceded by a ferromagnetic alloy electro-deposition using a commercially available NiFe solution. Selective deposition has been achieved using the bonding pad CMOS structure to polarize specified metallic areas. However, due to aluminum oxidation, direct adhesion of ferromagnetic alloy on the bonding pad was not possible. This problem has been solved by sputtering thin nickel seed layer.

Test results

Special design issues for strain gauges orientation have been addressed to achieve the best sensitivity. Finally a 45° serpentine gauge has been designed and successfully tested while orthogonal gauge exhibits no sensitivity (figure 8). The measured sensitivity of 210mV/T is comparable to the one of highly sensitive Hall effect sensor which consumes a 100µA current.
The sensor resolution has not been characterized yet. Nevertheless, it is worth noting that this device operated linearly only after full magnetization of the ferromagnetic material by the external magnetic field. For Permalloy (80%Ni and 20%Fe), the magnetization saturates when the magnetic field reaches 140A/m. In the air, this value corresponds to about 200µT.

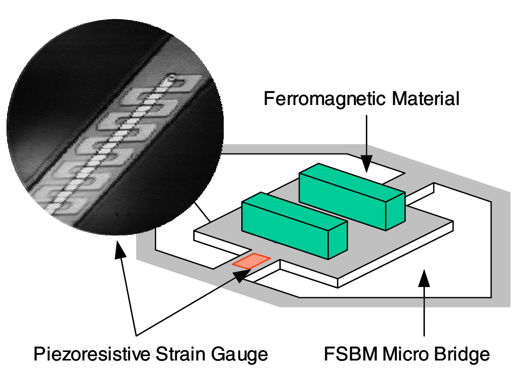

Fig. 7: The ferromagnetic prospective device with close-up view of the embedded 45° gauge.

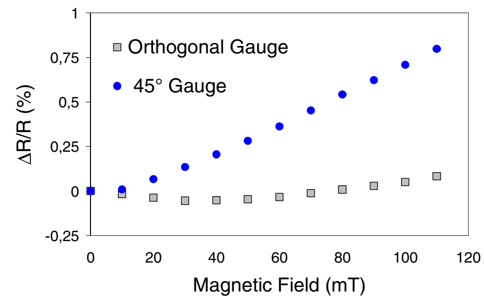

Fig. 8: Ferromagnetic sensor characterization results.

CONCLUSIONS

Two new CMOS electromechanical magnetic field sensors have been presented. The first device is a piezoresistive U-Shaped cantilever actuated by means of the Lorentz force. An electronic circuit has been designed to take benefit from mechanical resonance regarding the noise level and thus to improve sensitivity and resolution making such device suitable for navigation applications. It has been shown that in the context of monolithic MEMS fabrication, smart electronic design can provide cost-effective added value to the system in terms of performances. Further work concerns the integration of a second U-Shaped structure and dedicated electronics for 2-axis magnetic vector measurement with digital output.
The second introduced device is a prospective ferromagnetic sensor that requires no electrical power for actuation. Based on a piezoresistive torsional frame, an original gauge design has been validated. On the fabricated prototype, the measured sensitivity is very promising for such a passive sensor.

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